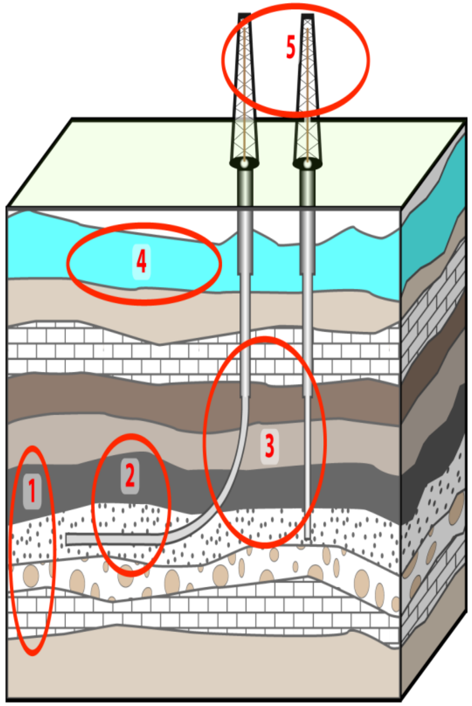
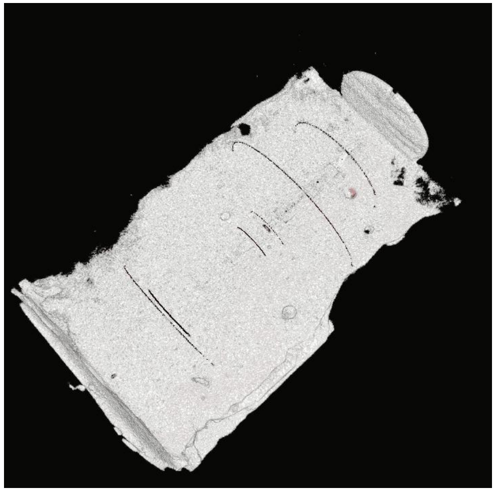
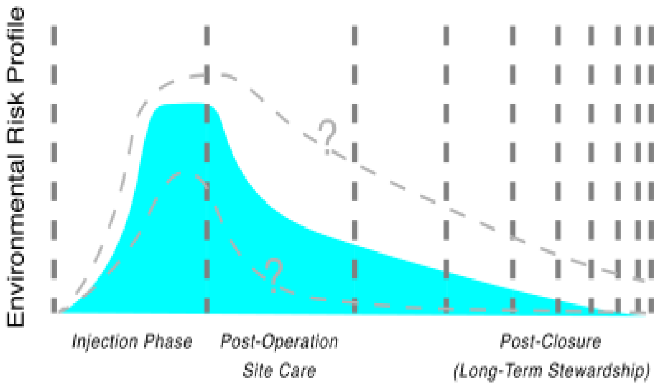






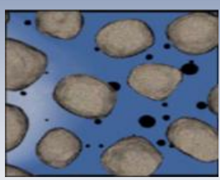
National Risk Assessment Partnership (NRAP)

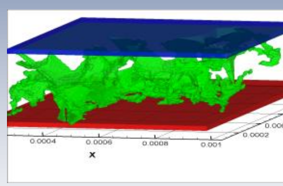
Grant S. Bromhal
NRAP Technical Coordinator
Geosciences Division

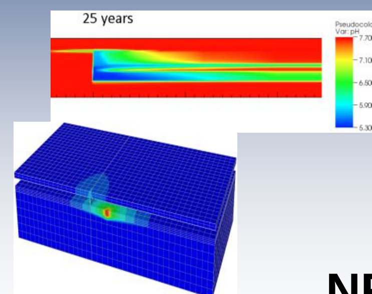
National Risk Assessment Program (NRAP)

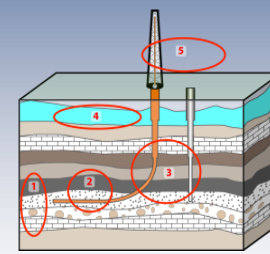
Develop a defensible, science-based methodology and platform for quantifying risk profiles at most types of CO_2 storage sites in order to guide decision making and risk management by reducing uncertainty in the business case for long-term storage.

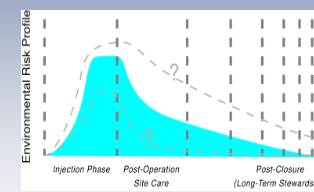
Elucidate key fundamental physics/chemistry → **Predict behavior of critical components** → **Predict system behavior (reservoir to receptor) over space and time** → **Quantify risk and safety relationships**











NRAP Technical Team

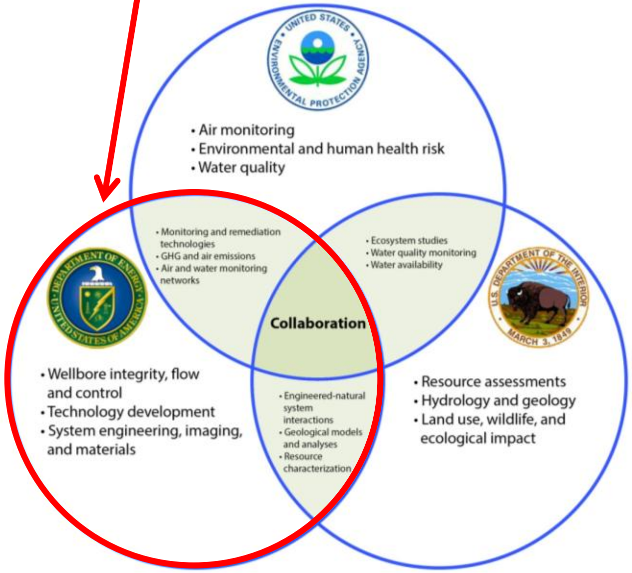
NRAP Stakeholder Group

Wade, LLC

National Risk Assessment Partnership:

Leveraging DOE's Science-Based Prediction Capability
to Build Confidence in Engineered–Natural Systems

- How effective is geologic storage of CO_2 (e.g., will it leak)?
- What is the value of potential long-term liabilities?
- What is the most effective and efficient approach to environmental monitoring post injection?
- What are the best protocols to mitigate potential for induced seismicity?



Two Key Goals

- develop toolset and supporting data for science-based risk assessments
    - ***already completed the first generation toolset to predict leakage impacts and potential for induced seismicity***
- build confidence in key storage-security relationships to support decisions
    - ***initiating phase to apply first generation toolset to elucidate storage-security relationships***

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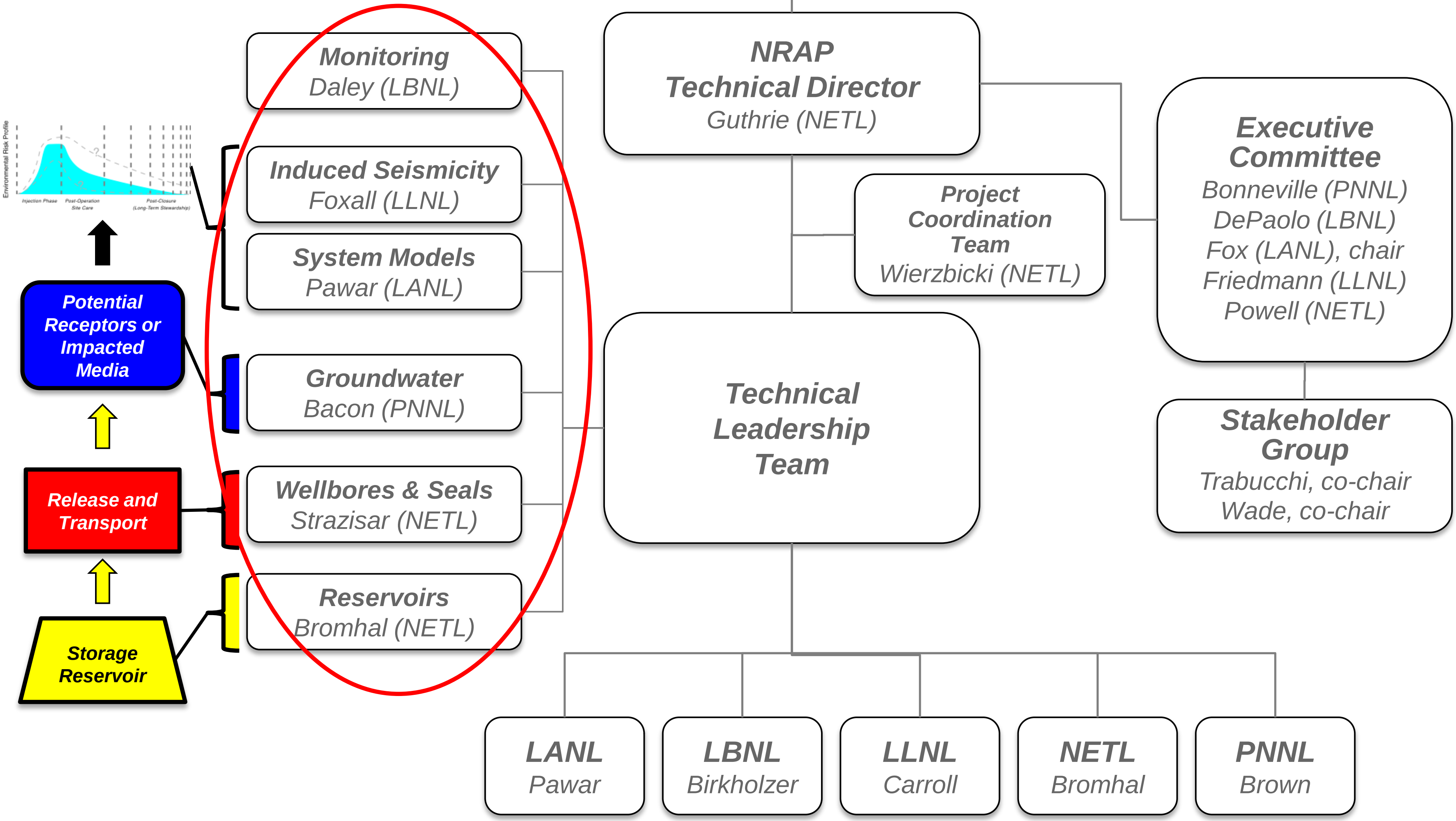
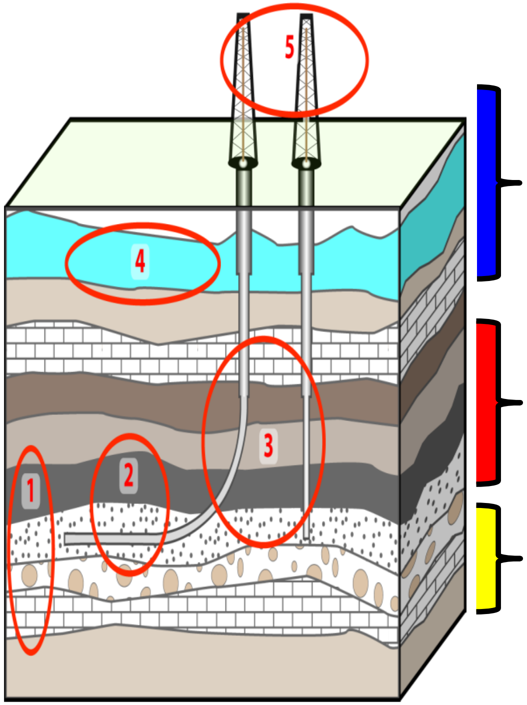
NRAP Organizational Structure

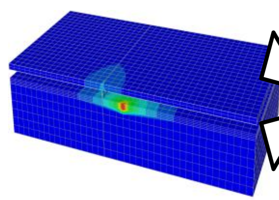


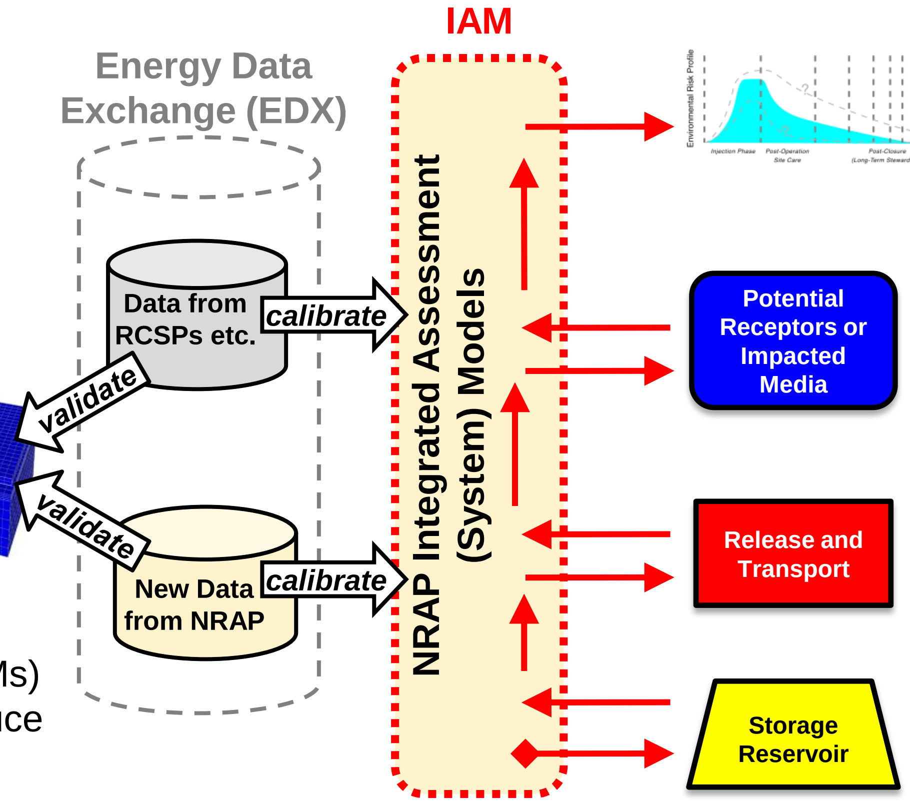
NRAP Approach to Quantifying System Performance

A. Divide system into discrete components



B. Develop detailed component models that are validated against lab/field data





C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions

D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk; calibrate using lab/field data from NRAP and other sources

E. Develop strategic monitoring protocols that allow verification of predicted system performance

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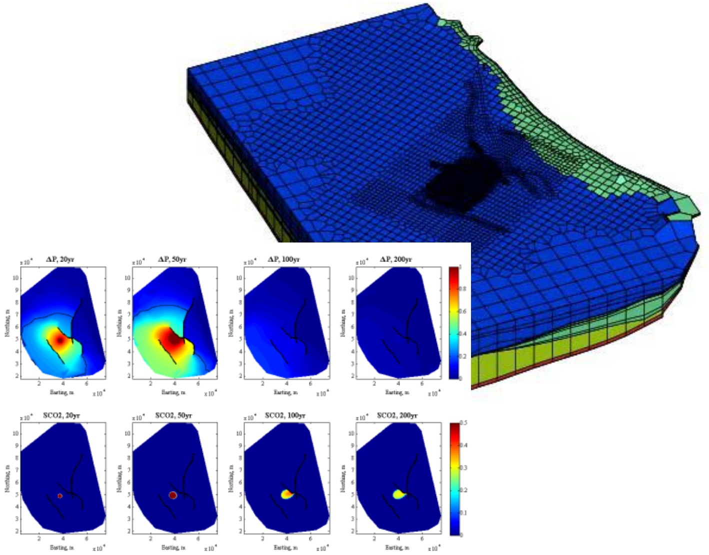
Reservoirs

Key NRAP Accomplishments/Results: Reservoirs

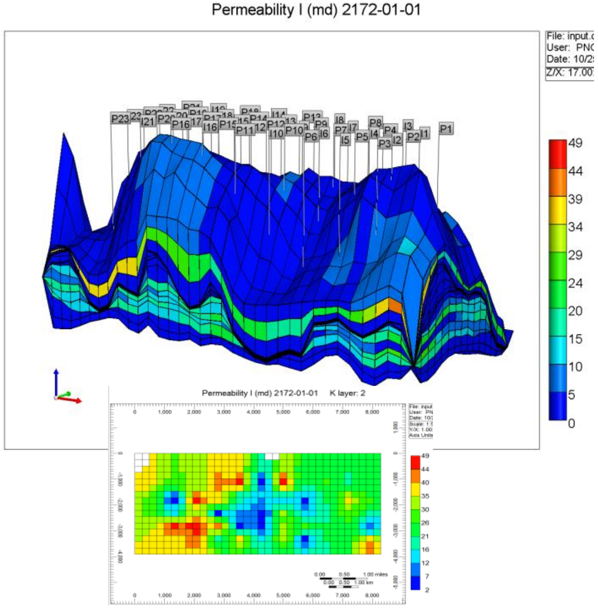
Tool & Method Development

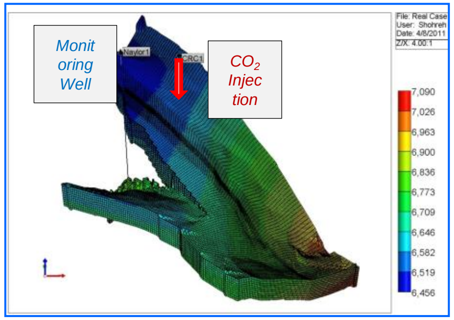
- Produced ROMs for three reservoirs
  - Kimberlina-like; 5 Mt/yr CO_2 (fixed) over 50 yrs injection only; 150 yrs relaxation; sandstone w/ interbedded shale & shale caprock
  - Otway-based; up to 0.5 Mt injection (variable rate) for 10 yrs; 500 yrs of relaxation; sandstone gas reservoir
  - SACROC-based; history-matched multiple well injection over 50 yrs; 1000 yrs of relaxation; carbonate reef EOR site
- Preliminary evaluations for 4 ROM approaches
  - Simple look up table
  - Surrogate reservoir model based on artificial intelligence
  - Polynomial chaos expansion
  - Gaussian regression analysis



General Trends & Relationships

- Pressure and saturation at reservoir-seal interface is sensitive to only a few key subsurface parameters
  - Caprock permeability is key in predicting pressure relaxation



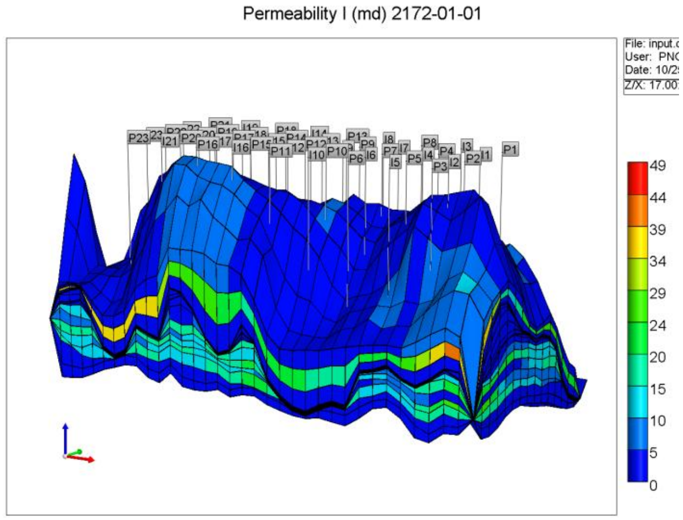


SACROC Oil Field Model

- **Saline Sandstone Reservoir Within Depleted Gas Field**
  - Based on actual EOR field in West Texas (40 years of CO_2 injection)
  - Upscaled porosity and permeability model from University of Utah
  - 10 CMG simulations with history-matched model, begin after oil production completed
  - Allow injection for 50 years in several wells at a given wellhead pressure
  - Surrogate model based on artificial intelligence and data mining approach using neural networks

Porosity

Permeability



Polynomial Chaos Expansion for SACROC ROM Development – Work in Progress

Inputs:
Time (t)
k1, k2, k3, k4,…
% of lithostatic pressure (pct)

↓

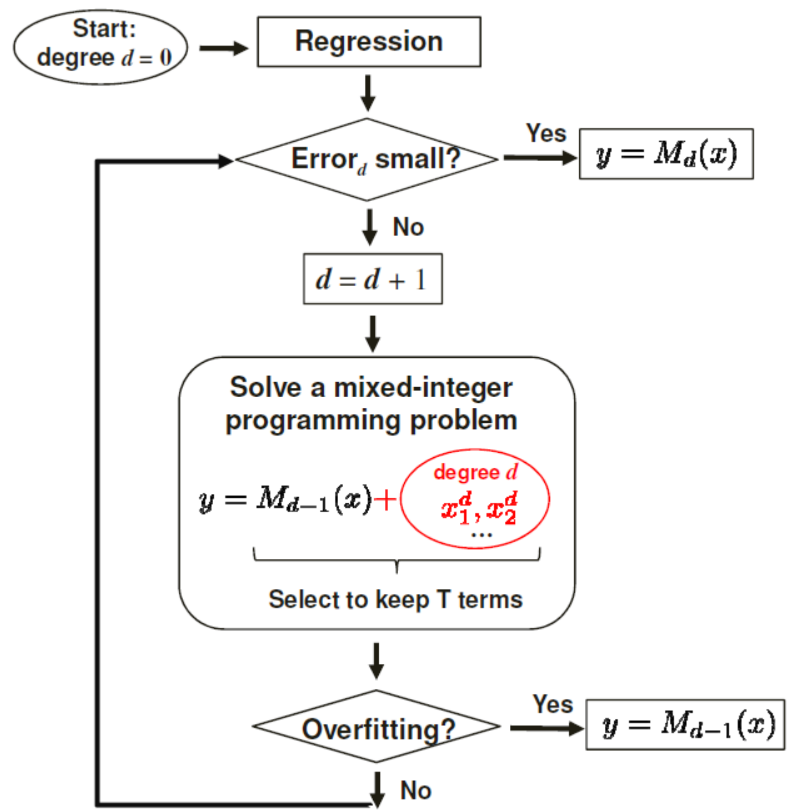
polynomial(k1,k2,k3,k4,…pct,t)

↓

Outputs of layer 18 gridblock:
- *Pressure*
- *Saturation(water, oil, CO_2)*

Total PCEs = 544 gridblocks × 4 outputs
= 2176 PCEs

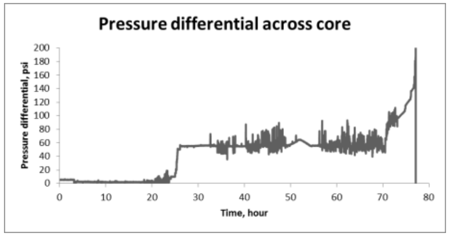
- *Steps:*
  1. *Design reservoir simulation inputs*
  2. *Reservoir simulation*
  3. *Train PCE model*

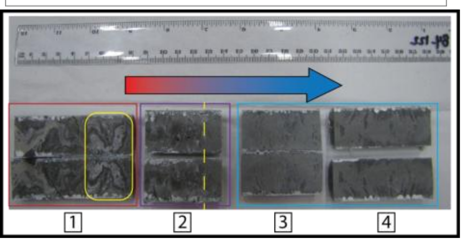


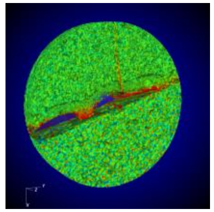
Migration Pathways
(Wellbores and Seals)

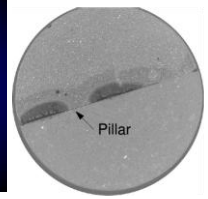
NRAP Migration Pathways Working Group

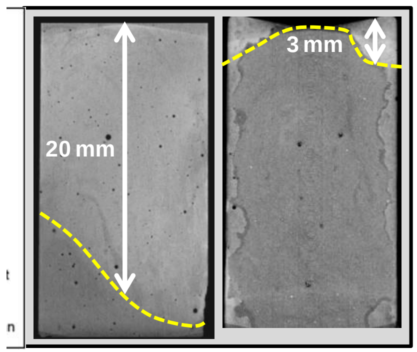
Laboratory Experiments to Address Science Gaps



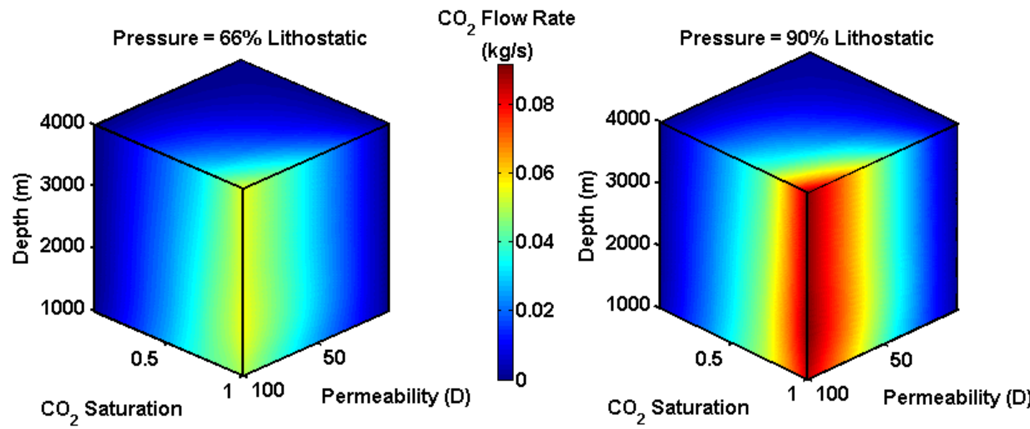




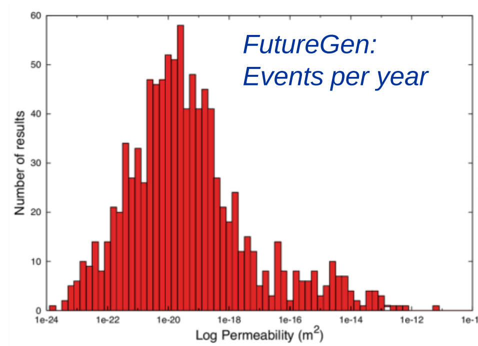


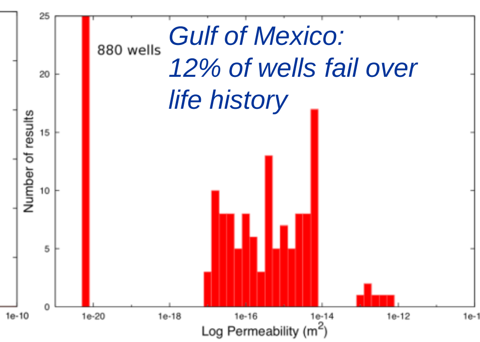


Well Scale Reduced Order Models for Risk Profiles

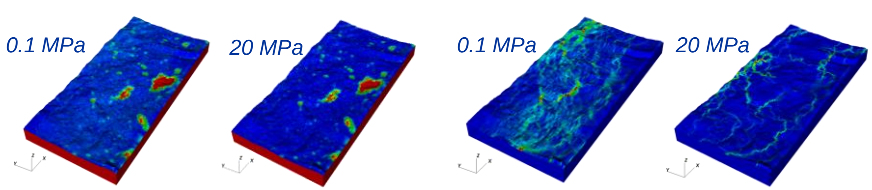


Field Data Analysis for Validation





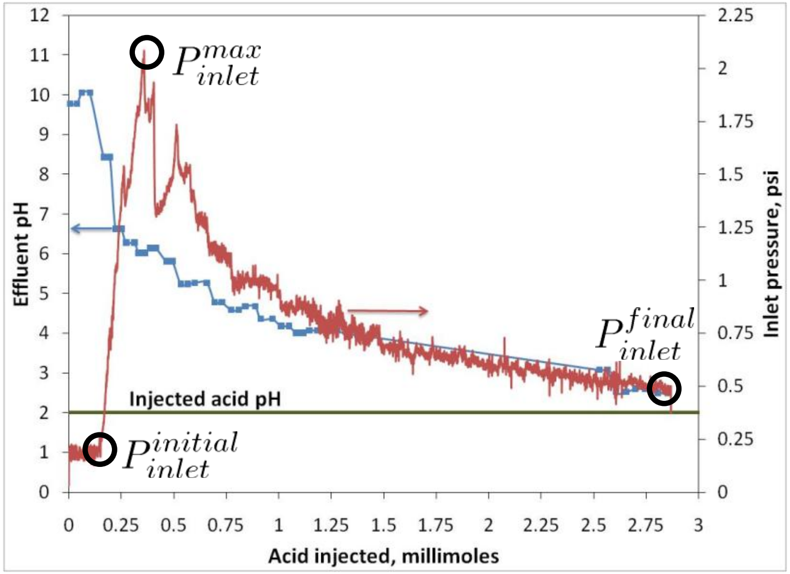
Single Fracture Models to Simulate Opening/Closing of Flow Paths

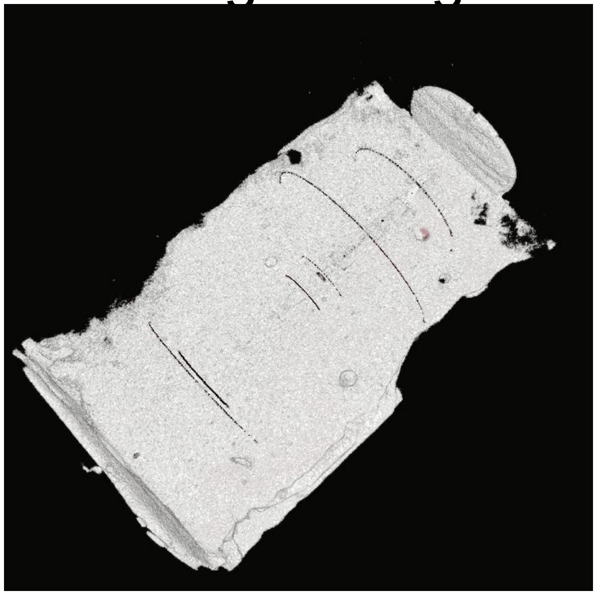


Aperture distributions (LHS) and pore-fluid velocities (RHS) from GEOS simulations of a natural fracture under atmospheric and 20 MPa confining pressure.

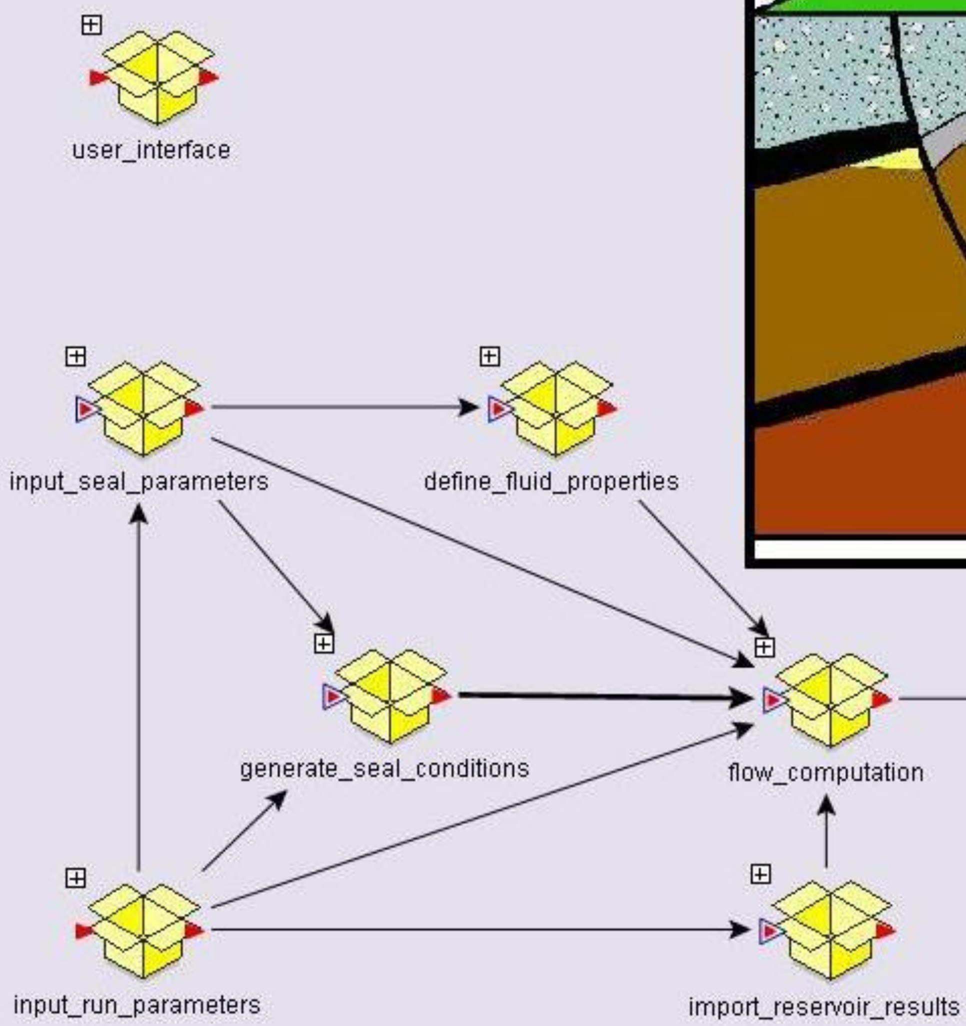
CO_2 and Wellbore Leakage Risk

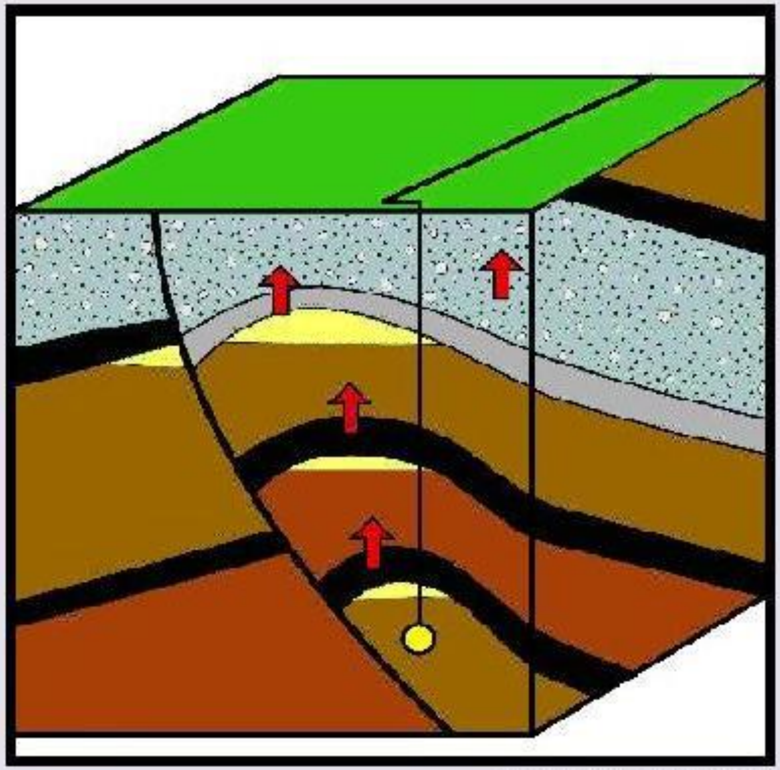
- Experimental and numerical studies of flow through damaged cements.
- Objective is to predict time-dependant leak rates.
- Provide evidence for self limiting or self enhancing leakage.





NSealR (NRAP Seal Barrier ROM)





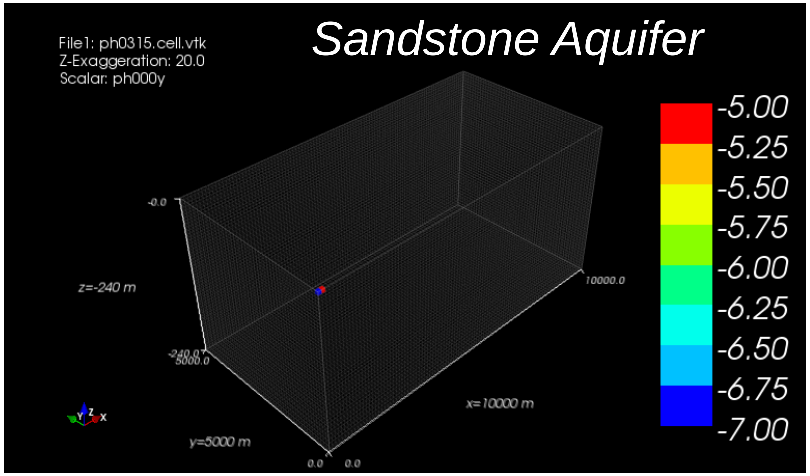
NETL Graphics Dept.(2012)

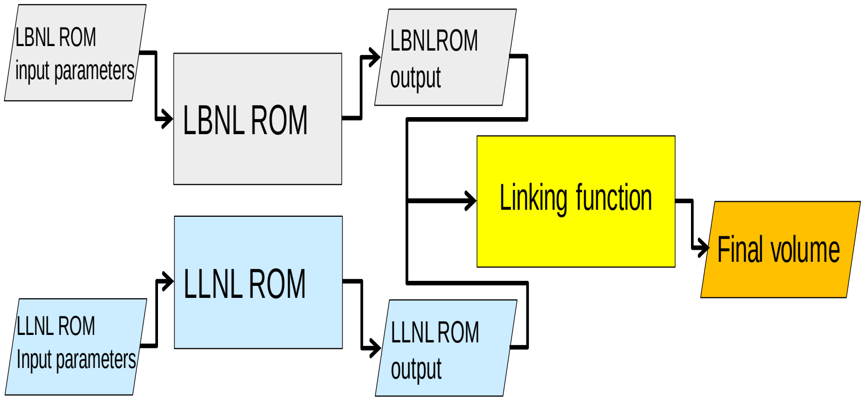
Groundwater

Key NRAP Accomplishments/Results: Groundwater

Tool & Method Development

- Established "no-impact" threshold values for two different classes of aquifers
  - High Plains confined sandstone aquifer
  - Edwards unconfined limestone aquifer
- Developed ROMs to predict impacts of CO_2 and brine leakage on pH, TDS and trace metals in each class of aquifer for MCL or "no-impact" thresholds
  - LLNL: sandstone, confined, 3D, multiple leaky wells, flow, transport, hydraulic heterogeneity, simple geochemistry
  - LBNL: sandstone, confined, 1D, complex geochemistry
  - LANL: limestone, unconfined, 3D, multiple leaky wells, flow, transport, hydraulic heterogeneity, simple geochemistry
  - PNNL: limestone, unconfined, 2D, complex geochemistry
- Developing linking functions to combine complex hydraulics and geochemistry ROMs for each class of aquifer
- Conducting experiments to determine impact of CO_2 leakage on major elements and trace metals using aquifer sediments from each class of aquifer





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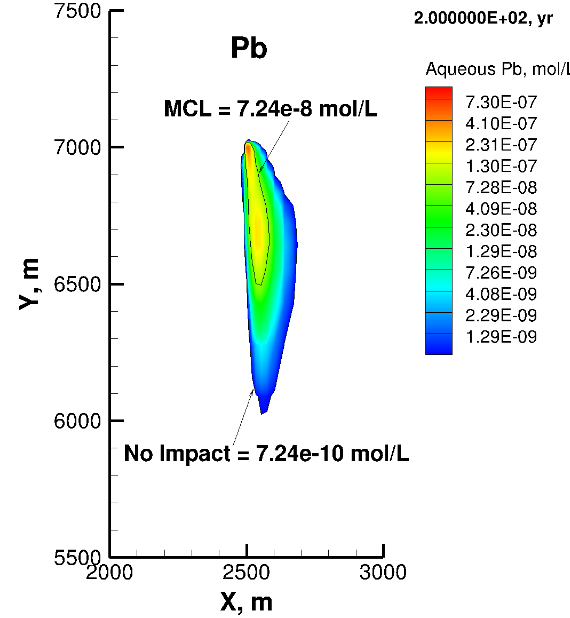
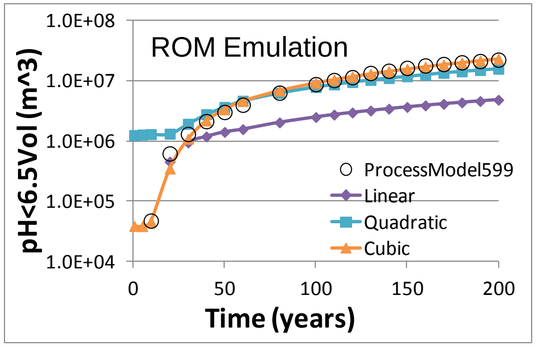
Key NRAP Accomplishments/Results: Groundwater

General Trends & Relationships

- Confined Sandstone Aquifer:
  - Adsorption/desorption is the most important process that controls trace-metal impacts due to the intrusion of CO_2
  - 0.01–0.1% of the CO_2 in the aquifer leaks to atmosphere
  - Developed relationships to assess impact of metal-transport by brine on aquifer chemistry (for Cd, As, Pb, Cr)
  - Chemical-Hydraulic linking function is a promising way to lower the computation load for derivation of ROM and improve prediction of volume affected by CO_2 intrusion
- Unconfined Limestone Aquifer:
  - Volume of pH impact is sensitive to CO_2 leak rate, total CO_2 mass, porosity and permeability
  - Leak rates are most significant parameters for pH, TDS and trace metal concentrations, but carbonate equilibria and clay sorption are also important
  - 69% of simulations have CO_2 atmospheric leak rates >0 and 52% of simulations have atmospheric leak rate >80% of wellbore leak rate
  - Plume sizes for trace metals are notably larger using no-impact thresholds
  - The quadratic and cubic ROMs for the 8 output variables are the best models and can be used for system-level predictions of hydraulic impacts

Limestone Aquifer





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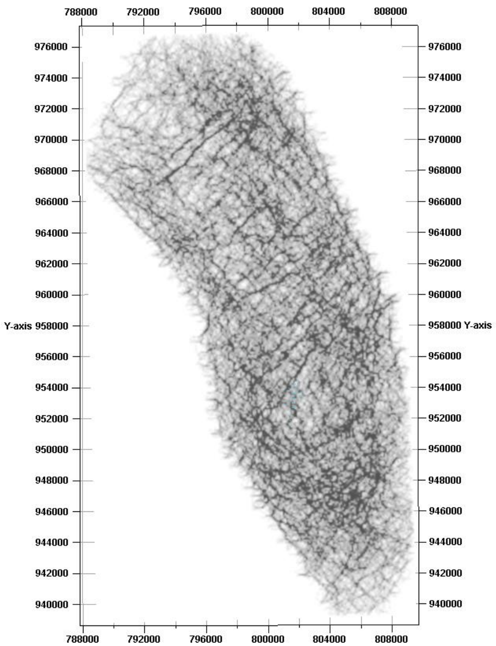
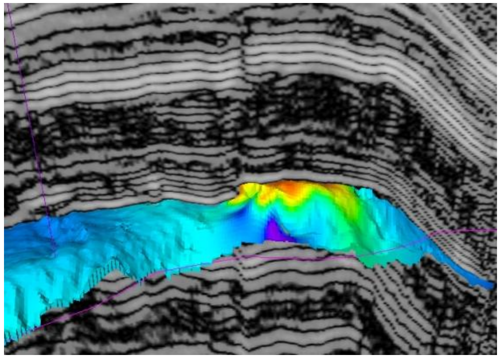
Monitoring

Fault and Fracture Zone Detection and Reduced Order Fracture Model Development for Risk Assessment

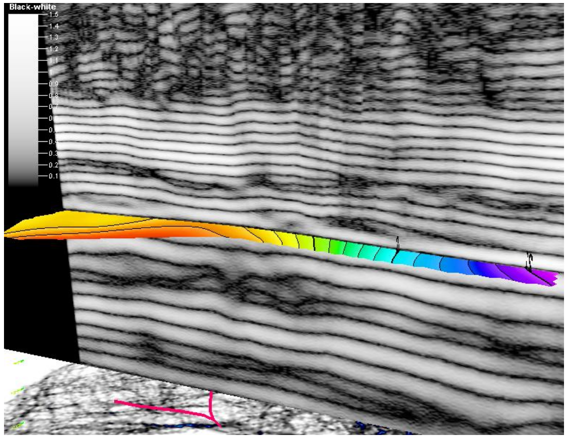


Teapot Dome

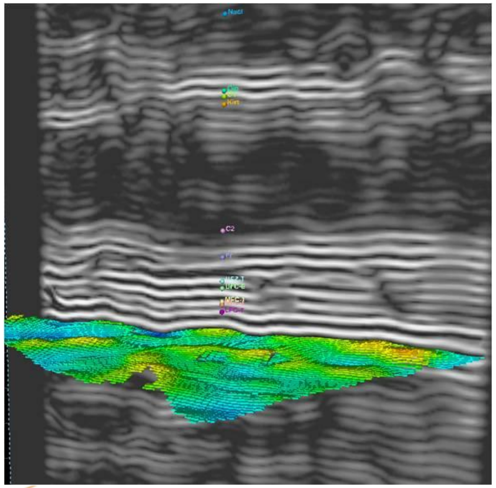


Post-stack enhancements adaptive to non-stationary signal

Appalachian Foreland, CONSOL/ZERT Pilot

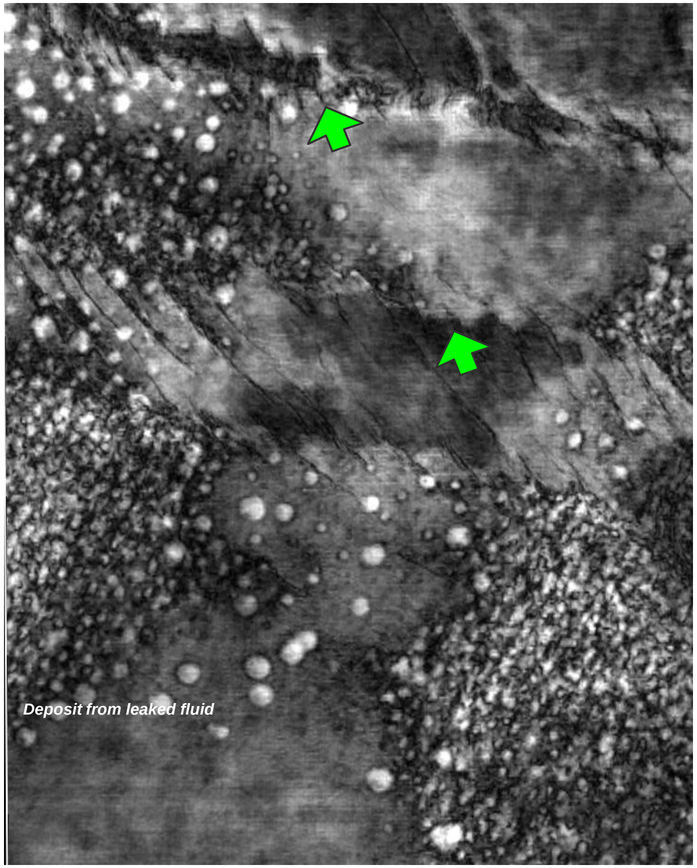


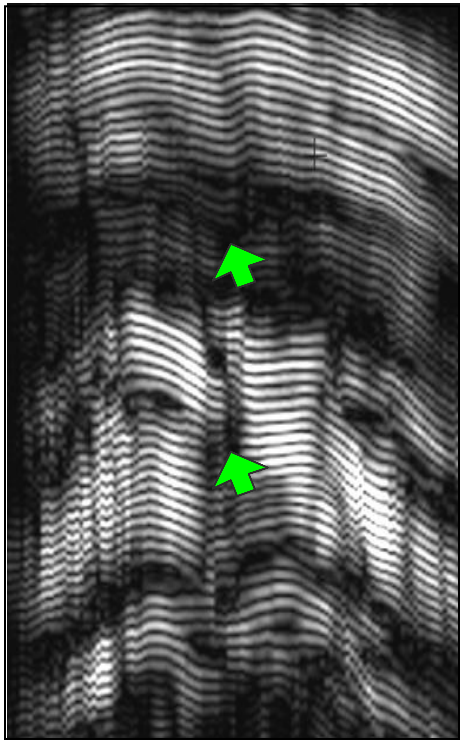
San Juan Basin Pilot

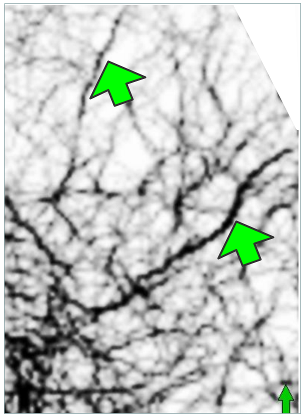


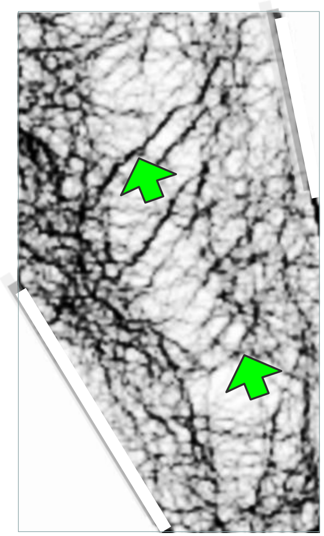
Our efforts have been used to enhance possible fracture zones and fault networks and to identify potential leakage zones in three areas including the San Juan Basin (New Mexico), Teapot Dome (Wyoming) and the Central Appalachian foreland (West Virginia).

Waveform Attribute Analysis to Detect Potentially Leaky Faults









Test case in a fractured reservoir. Note the enhanced imagery of reservoir and cap rock fractures

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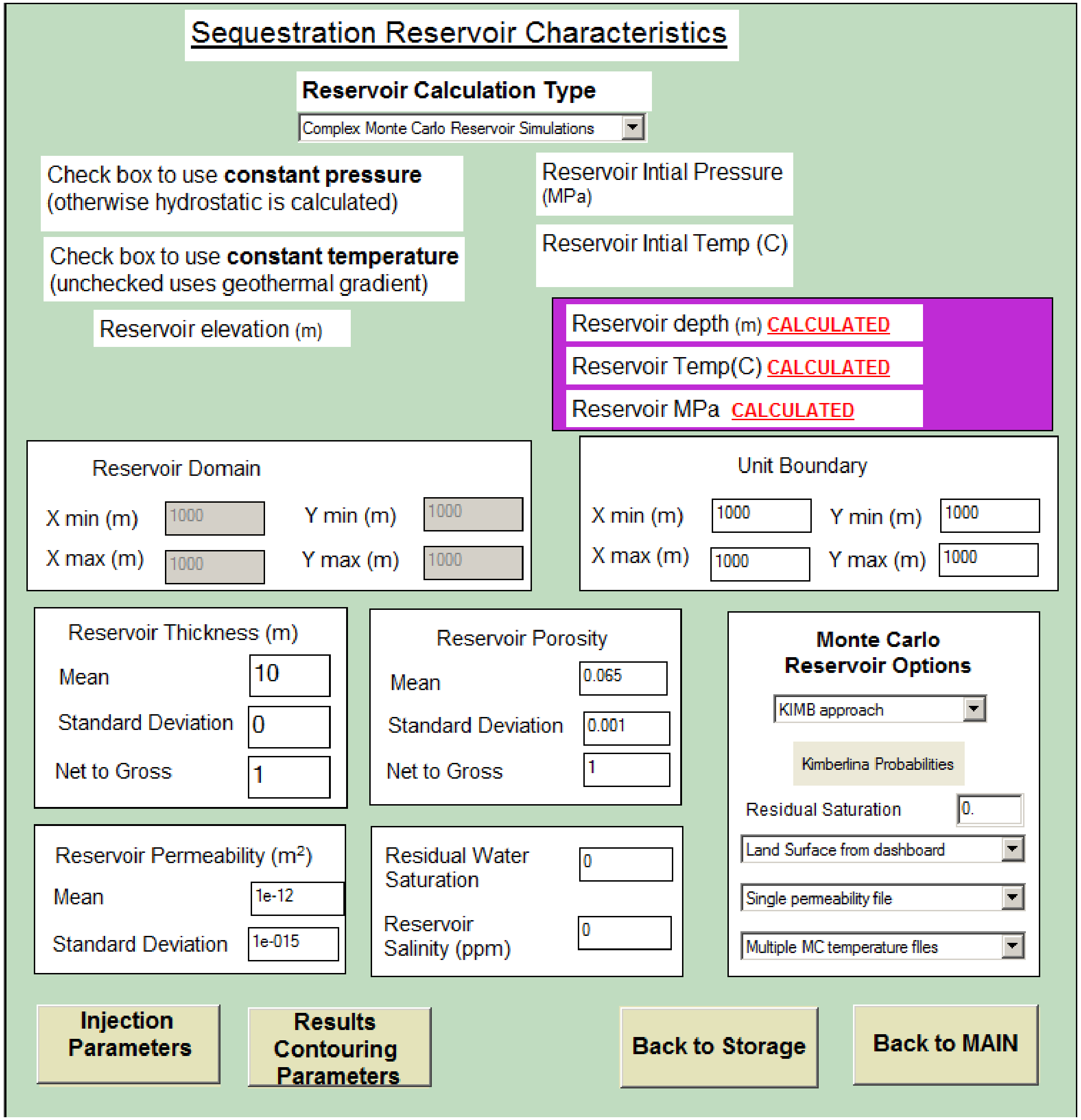
Systems Modeling

Reservoir Dashboard



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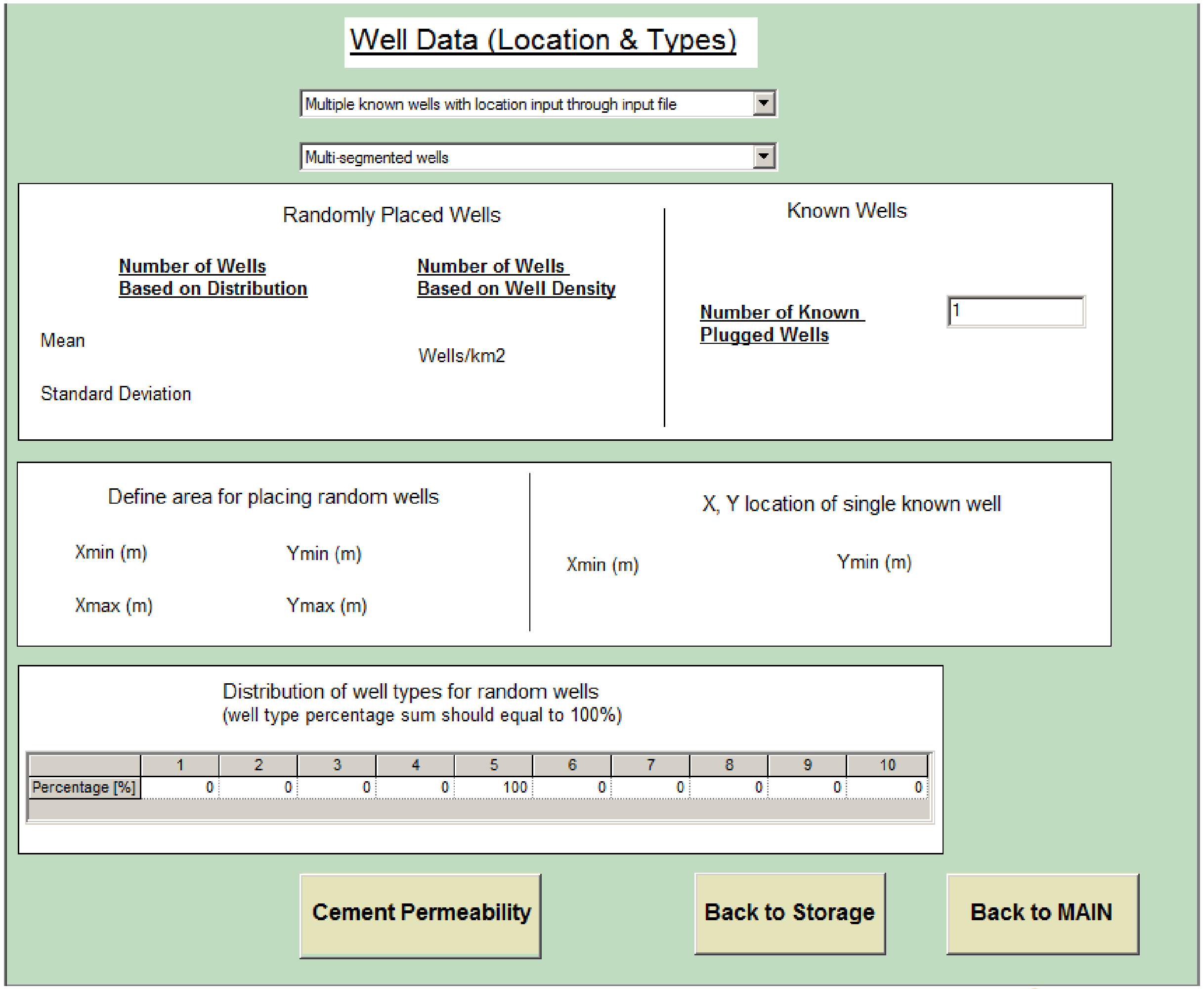
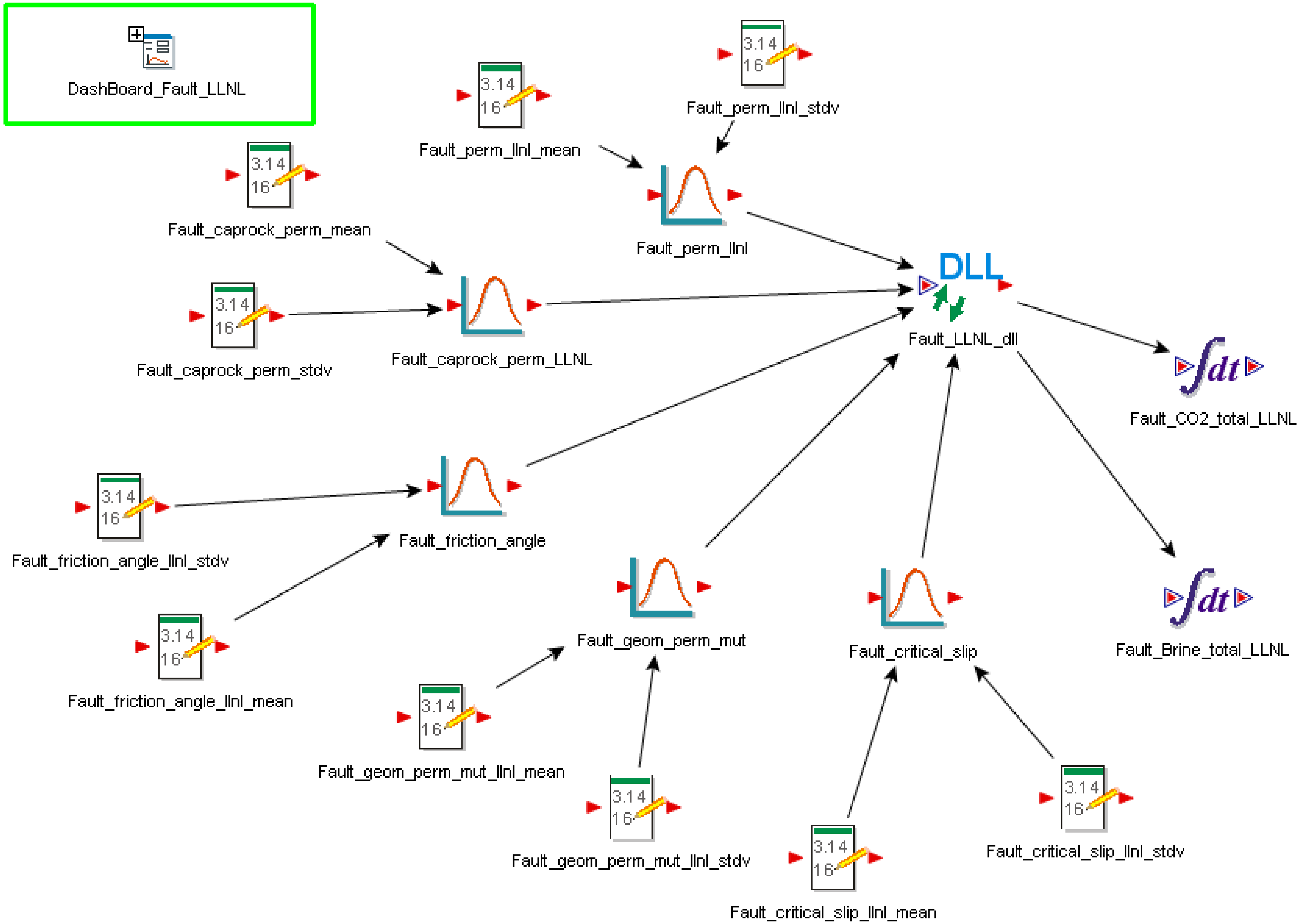
Wellbore

- Updated the well data input dashboard

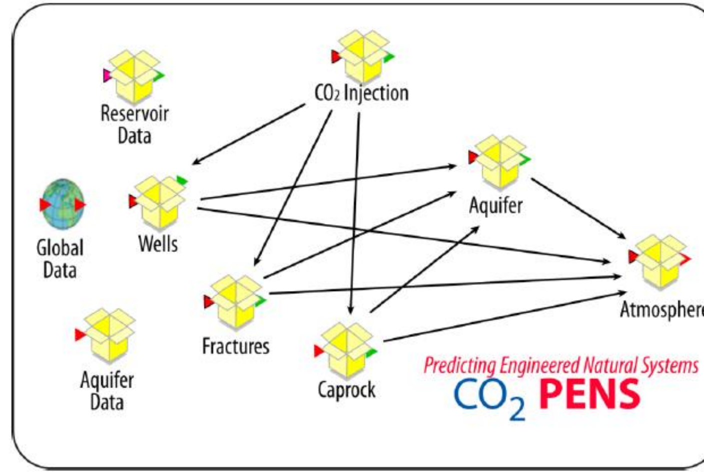


Fault

Fault ROM dll in CO_2-PENS

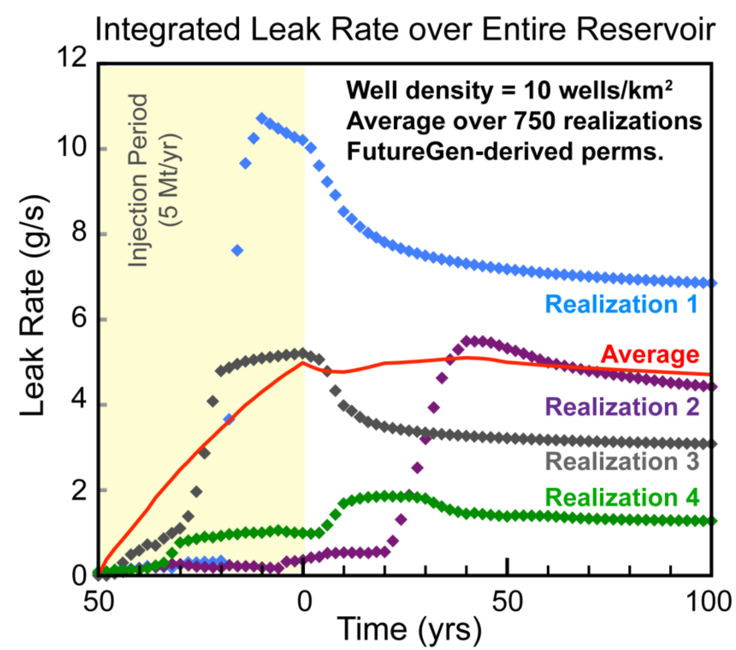


Key NRAP Accomplishments/Results: System Models



Tool & Method Development

- Developed first-ever integrated assessment model for predicting for leakage impacts
  - Approach integrated ROMs for storage reservoir, wellbores (open & cemented), faults and shallow aquifer
  - IAM used to generate risk profiles and associated uncertainties for three metrics (release to atmosphere, change in pH in shallow aquifer, change in TDS in shallow aquifer)
- Developed second generation IAM for leakage impacts
  - Updated first generation IAM with second generation ROMs
  - Second generation ROMs have increased process complexities and wider parameter range



General Trends & Relationships

- Leakage Impacts
  - The calculated risk profiles show significantly different qualitative behavior compared to “Benson” profile
  - “Preliminary” risk profiles show extremely low risks for the three leakage metrics considered for first generation
  - Uncertainties in wellbore cement permeability dominate overall uncertainties

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Induced Seismicity

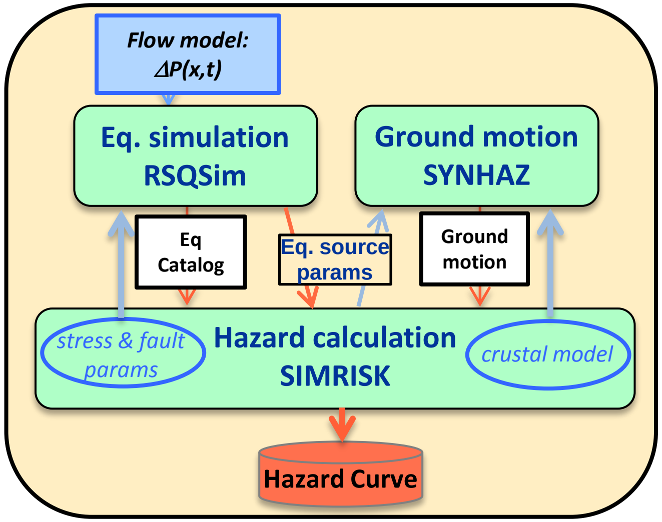
Key NRAP Accomplishments/Results: Induced Seismicity

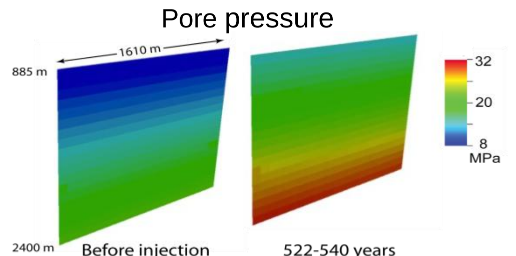
Tool & Method Development

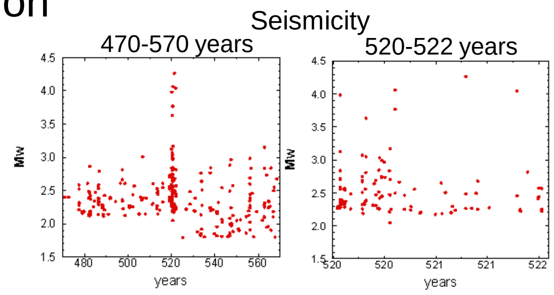
- Developed first-ever probabilistic seismic hazard assessment (PSHA) tool for induced seismicity
  - adapted widely accepted conventional PSHA approach
- Extending development to assess damage and nuisance (felt event) risks
  - demonstration application to realistic CO_2 injection scenarios

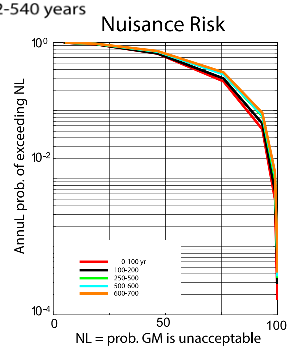
General Trends & Relationships

- Rates of occurrence and sizes of earthquakes are determined by tectonic stress and reservoir pressure
  - sensitive to fault permeability and a few key parameters in the law governing the evolution of fault frictional strength
- Risk of CO_2 leakage may be affected by slip on faults during earthquakes, requires integration with systems leakage model









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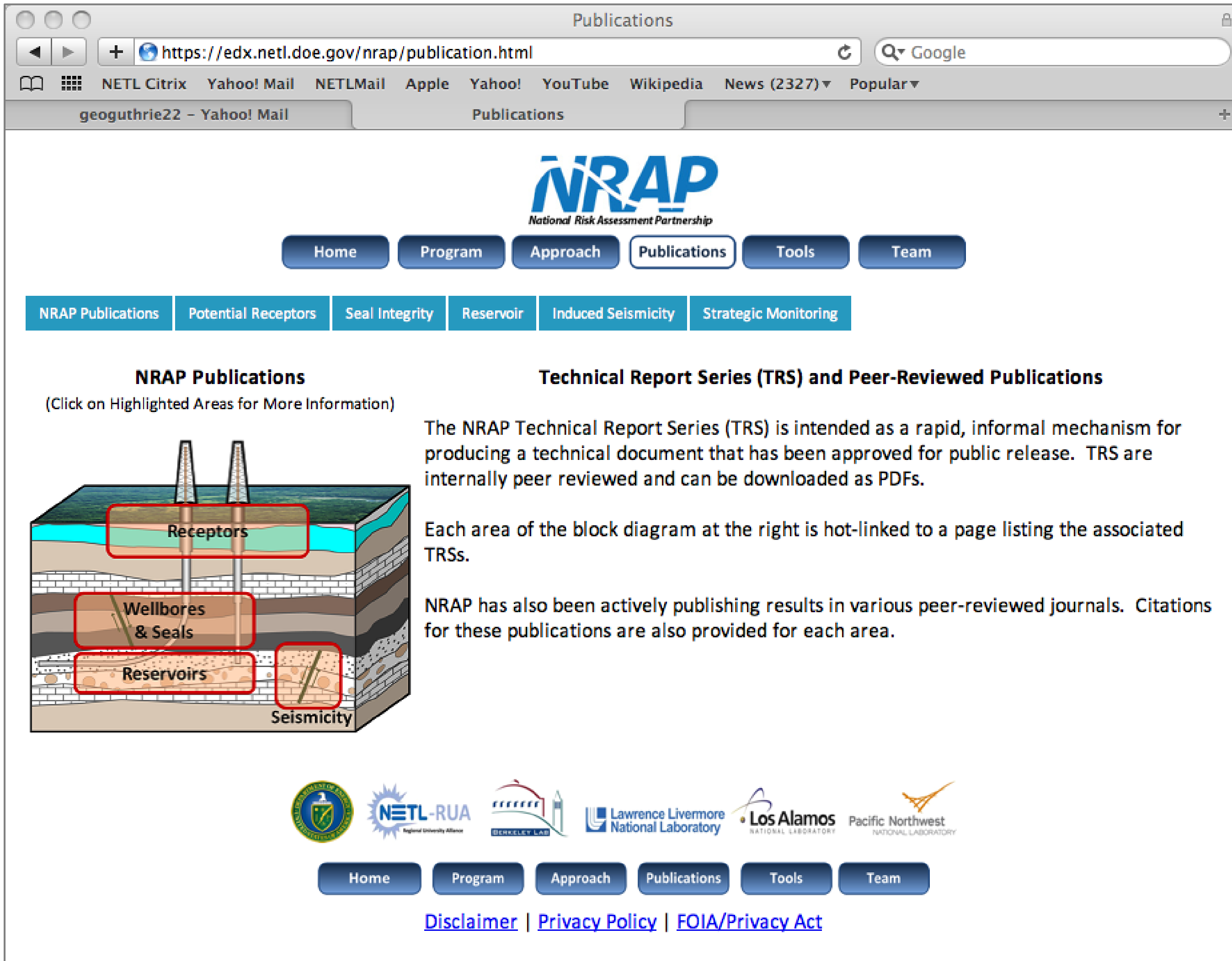
Energy Data eXchange is being used as tech transfer mechanism for technical reports, tools, and datasets.



NRAP Team Members

Rajesh Pawar, Grant Bromhal, Robert Dilmore, Jason Gastelum, Edwin Jones, Jason Monnell, Curt Oldenburg, Philip Stauffer, Yingqi Zhang, Liange Zheng, Marco Bianchi, Jens Birkholzer, Nicolas Spycher, Susan Hubbard, Preston Jordan, Peter Nico, John Peterson, Charu Varadharajan, Yuxin Wu, Susan Carroll, Yue Hao, Kayyum Mansoor, Yunwei Sun, and Sharon Torres, Elizabeth Keating, Zhenxue Dai, Dennis Newell, and Hari Viswanathan, Alexandra Hakala, Christina Lopano, Athanasios Karamalidis, Maneesh Sharma; Rosemary Capo, Brian Stewart, James Gardiner; Craig Griffith, Diana Bacon, Chris Brown, Kirk Cantrell, Omar Harvey, George Last, Chris Murray, Nik Qafoku, and Hongbo Shao, Angela Goodman, Shahab Mohaghegh, Shohreh Amini, Vidi Gholami, Alireza Shahkarami, Nick Sahinidis, Yan Zhang, Wei Jia, Brian McPherson, Jens Birkholzer, Haruko Wainwright, Yingqi Zhang, George Pau, Chris Doughty, Quanlin Zhou, Stefan Finsterle, Susan Carroll, Yue Hao, Chuanhe Lu, Diana Bacon, Mark White, Yilin Fang, Kirk Cantrell, Rajesh Pawar, Phil Stauffer, Hailin Deng, Brian Strasizar, Bill Carey, Bill Harbert, Dengling Gao, Tom Wilson, Erik Westman, Hema Siriwardane, Josh White, Bill Foxall ++

Questions?

- **Thanks!**

- **bromhal@netl.doe.gov**